LA-UR-02-7694

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Submitted to: DANCE project

Cost effective (n,γ)-experiments with natural samples at DANCE

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1. Introduction

The DANCE array is designed to measure neutron capture cross sections of unstable nuclei close to the valley of stability. An experiment will take typically between 1 and 2 weeks per isotope. The production of radioactive samples of a few milligrams is much more time consuming. Therefore there will be beam time, which can not be reasonably used measuring radioactive isotopes.
On the other hand, there is a need for accurate neutron capture data in the keV-range even for many stable isotopes [1].
The good energy resolution, the high detection efficiency of DANCE, and the wide neutron energy range at LANSCE will provide a tool to measure many important cross section data without the need of preparing isotopically enriched samples, that are usually expensive and difficult to handle.

2. Method

All of the elements with an odd proton number have two or less stable isotopes, and some of the even proton elements have also 4 or less stable isotopes. This leads to the idea of measuring (n,γ) cross sections of elementally separated instead of isotopically enriched samples.
The total energy released after a neutron capture (Q-value) as well as the multiplicity (number of released γ-rays) distribution depends on the specific isotope. The DANCE detector, a 4π-array of 160 BaF_2 crystals, has an energy resolution of about 7 % at 1 MeV γ-ray energy and is therefore able to distinguish between Q-values, that have a difference of more than 200 keV. The high granularity also helps to distinguish between different isotopes, since simulations have shown, that there are correlations between the number of γ-rays emitted and the number of detectors which have fired [2-4]. Finally the properties of the white neutron source at LANSCE, providing neutrons from thermal energies up to several hundred MeV, can be used to determine the DANCE-response to neutron captures on a specific isotope very accurately, since basically all nuclei show resonance behavior in the eV-neutron energy range. The energy and multiplicity distribution, following an (n,γ)-event in one of the isotopes contained in the sample, can be calibrated at the known resonances, where the cross section is often several orders of magnitudes higher, meaning that in certain energy intervals one isotope dominates the observed signal entirely. This information can be used to determine the exact yield ratio even at higher energies.
The method could be improved even by optimizing the combination of theoretical simulation cascades with the detector response functions. The successful measurement of the neutron capture cross section of ^{180}Ta, which was carried out with a 5.5 % enriched Ta-sample in Karlsruhe [5], serves as a proof of principle experiment.

3. Isotopes and elements of interest

Generally speaking, there have been basically two sources of high accuracy (better than 5 %) neutron capture data in the astrophysically interesting keV-range: TOF measurements at the Karlsruhe 4π BaF_2 detector and activation experiments. Most of the experiments at the Karlsruhe detector are done on stable isotopes of even proton numbers, since such isotopic chains are often affected by s-process branchings. Activation measurements have been performed throughout the chart of nuclides depending on the radioactivity properties of the capture product. The neutron energy range for the TOF experiments is 5 – 250 keV. Due to the nature of activation experiments only integrated energy information is available.
This means, valuable nuclear astrophysics information still needs to be measured on almost every isotope with an odd proton number.
The following table contains information about almost all stable elements with an odd number of protons and some with an even proton number with just a few stable isotopes.

- The first column corresponds to the name of the element,
- the second to the atomic mass of the respective isotope,
- the third to the natural isotopic abundance (see e.g. [6]),
- the 4th / 5th to the Maxwellian averaged cross section and its uncertainty at kT = 30 keV [1],
- the 6th the count rate ratio assuming a natural sample and 30 keV neutrons,
- the 7th a comment about the origin of the cross section data. If nothing else is mentioned the data are from TOF-experiments at white neutron sources.
- The 8th column indicates, whether more data would be valuable because either the uncertainties quoted are not satisfactory or the energy range is restricted,
- and the last column indicates if a measurement at DANCE with a sample natural composition would provide new data.

El.	Isot.	Q-value	Isot. Abund.	(n,γ) cross section [1]	uncert.	count ratio	comment	more needed	feasible (DANCE)
		(keV)	(%)	(mb)	(%)				
O	16	4143	99.762	0.038	10.53	**100**		**y**	
	17	8044	0.038			**0**			
	18	3956	0.2	0.0089	9.03	**0**	Activation	**y**	**(only = 16)**
F	19	6601	100	5.8	20.69			**y**	**y**
Ne	20	6761	90.48	0.119	9.24	**92**		**y**	
	21	10364	0.27	1.5	60.00	**3.5**		**y**	
	22	5201	9.25	0.059	10.17	**4.7**		**y**	**y**
Na	23	6959	100	2.1	9.52			**y**	**y**
Mg	24	7331	78.99	3.3	12.12	**80**		**y**	
	25	11093	10	6.4	6.25	**20**		**y**	
	26	6443	11.01	0.126	7.14	**0.4**	Activation	**y**	**y, 24 / 25**
Al	27		100	3.74	8.02			**n**	**y**
Si	28	8474	92.23	2.9	10.34	**82**		**y**	
	29	10609	4.67	7.9	11.39	**11**		**y**	
	30	6587	3.1	6.5	9.23	**6.2**		**y**	**y**
P	31		100	1.74	5.17			**n**	**y**
S	32	8642	95.02	4.1	14.63	**98**		**y**	
	33	11417	0.75	7.4	20.27	**1.4**		**y**	
	34	6986	4.21	0.226	4.42	**0.2**	Activation	**y**	
	36	4304	0.02	0.171	8.19	**0**	Activation	**y**	**y, 32 / 33**
Cl	35	8580	75.77	10	3.00	**94**		**n**	**y**

	37	6108	24.23	2.15	3.72	**6.4**		**n**	
Ar	36	8789	0.337	9	16.67	**1.2**	theoretical	**y**	
	38	6598	0.063	3	10.00	**0.1**	theoretical	**y**	
	40	6099	99.6	2.6	76.92	**99**		**y**	**y, 36 / 40**
K	39	7800	93.258	11.8	3.39	**88**		**y**	
	40	10095	0.0117	31.7	22.08	**0**	theoretical	**y**	
	41	7534	6.7302	22	3.18	**12**		**n**	**y, 39 / 41**
Sc	45		100	69	7.25			**y**	**y**
V	50	11051	0.25	50	18.00	**0.3**	theoretical	**y**	
	51	7311	99.75	38	10.53	**100**		**y**	**y**
Cr	50	9262	4.435	49	26.53	**14**		**y**	
	52	7939	83.789	8.8	26.14	**48**		**y**	
	53	9719	9.501	58	17.24	**36**		**y**	
	54	6246	2.365	6.7	23.88	**1**		**y**	**y, 50 / 52 / 53**
Mn	55	7270	100	39.6	7.58			**y**	**y**
Fe	54	9298	5.8	27.6	6.52	**12**		**y**	
	56	7646	91.72	11.7	4.27	**81**		**n**	
	57	10044	2.2	40	10.00	**6.6**		**y**	
	58	6581	0.28	12.1	10.74	**0.3**		**y**	**y, 54 / 56 / 57**
Co	59	7492	100	38	10.53			**y**	**y**
Cu	63	7916	69.17	94	10.64	**84**		**y**	
	65	7066	30.83	41	12.20	**16**		**y**	**y**
Ga	69	7655	60.108	139	4.32	**63**		**n**	
	71	6521	39.892	123	6.50	**37**	Activation	**y**	**y**
As	75	7328	100	586	5.97		Activation	**y**	**y**
Br	79	7892	50.69	627	6.70	**67**	Activation	**y**	
	81	7593	49.31	313	5.11	**33**	Activation	**y**	**y**
Rb	85	8651	72.165	240	3.75	**98**	Activation	**y**	
	87	6082	27.835	15	10.00	**2.4**	Activation	**y**	**y, 85**
Sr	84	8530	0.56	368	34.24	**10**	theoretical	**y**	
	86	8428	9.86	64	4.69	**32**		**y**	
	87	11113	7	92	4.35	**32**		**y**	
	88	6359	82.58	6.2	4.84	**26**		**y**	**y, 87 / 88**
Y	89	6857	100	19	3.16		Activation	**y**	**y**
Nb	93	7227	100	266	1.88			**n**	**y**
Rh	103	6999	100	811	1.73			**n**	**y**
Ag	107	7270	51.839	792	3.79	**52**	Activation	**y**	
	109	6809	48.161	788	3.81	**48**		**n**	**y**
In	113	7274	4.3	787	8.89	**4.8**		**y**	
	115	6784	95.7	706	9.92	**95**		**y**	**y**
Sb	121	6807	57.36	532	3.01	**70**	Activation	**y**	
	123	6467	42.69	303	2.97	**30**	Activation	**y**	**y**
I	127	6826	100	635	4.72			**y**	**y**
Cs	133	6892	100	509	4.13			**n**	**y**
La	138	8778	0.0902	0.85	50.00	**0**	theoretical	**y**	
	139	5161	99.91	38.4	7.03	**100**	Activation	**y**	**only 139**
Ce	136	7481	0.19	328	6.40	**4.5**	Activation	**y**	
	138	7456	0.25	179	2.79	**3.2**	Activation	**y**	
	140	5429	88.48	11	3.64	**70**	Activation	**y**	
	142	5145	11.08	28	3.57	**22**	Activation	**y**	**y, 140/142**
Pr	141		100	111.4	1.26			**n**	**y**
	151	6307	47.8	3775	3.97	**55**	Activation	**y**	
MSN **Eu**	153	6442	52.2	2780	3.60	**45**	Activation	**y**	**y**
Tb	159	6375	100	1580	9.49			**y**	**y**
Ho	165		100	1280	7.81			**y**	**y**
Tm	169		100	1129	4.96			**y**	**y**

Lu	175	6288	97.41	1146	3.84	**97**		**y**	
	176	7072	2.59	1532	4.50	**3.4**		**y**	**y**
Re	185	6180	37.4	1535	4.04	**44**	Activation	**y**	
	187	5872	62.6	1160	4.91	**56**	Activation	**y**	**y**
Ir	191	6198	37.3	1350	3.19	**45**	Activation	**y**	
	193	6067	62.7	994	7.04	**55**	Activation	**y**	**y**
Tl	203	6656	29.524	124	6.45	**49**		**y**	
	205	6504	70.476	54	7.41	**51**		**y**	**y**
Bi	209		100	2.7	18.52			**y**	**y**

4. Conclusions

The use of natural samples at DANCE is a promising attempt to fulfill the need for accurate nuclear data over a wide range of isotopes as well as to increase the number of experiments per year carried out at DANCE. Natural samples can be provided with masses up to 100 mg, which means run times between several hours and a few days are sufficient to collect enough statistics for uncertainties of a few percent.

The very first samples could be mono-isotopic and self-supporting, e.g., scandium, manganese, or cobalt.

The first multi-isotopic samples should be at least self-supporting. Promising cases are copper and vanadium.

5. References

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